THE EFFECT OF CYCLIC RELATIVE HUMIDITY CHANGES ON MOISTURE CONTENT AND THICKNESS SWELLING BEHAVIOR OF ORIENTED STRANDBOARD

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(Received May 2009)

Abstract. This study examines the effect of cyclic RH exposure on MC and thickness swelling (TS) of oriented strandboard (OSB) made from fire-impacted trees. Two specimens were cut from the center of each OSB panel and one was edge-sealed. After being conditioned to 65% RH, specimens were placed in a climate-controlled chamber and subjected to three cyclic changes of 90 – 30% RH at 20°C. Experimental data were characterized by three time-dependent MC or TS models: logarithmic, power law, and exponential. The latter two models gave the best fits showing that edge-sealing reduced the extent of swelling during adsorption and reduced the moisture loss at desorption. The models also described the effect of burnt level and bark throughout the humidity exposure cycles. The exponential model revealed no significant effect of burnt level on the panel TS. Both the power law and exponential models indicated that addition of charred bark to the panels significantly decreased the maximum amount of moisture and thickness change. The exponential model revealed an increase in equilibrium TS at the end of each RH cycle compared with the end of precyclic desorption. True nonrecoverable TS was difficult to discern in Cycle 1 because of moisture hysteresis, but the nonrecoverable effect was evident in Cycles 2 and 3.

Keywords: Fire-impacted wood, oriented strandboard, cyclic humidity exposure, thickness swelling modeling.

INTRODUCTION

The effects of moisture on wood panel dimensional stability are commonly studied following standard test procedures. Two such tests outlined in ASTM D1037 are frequently used: water absorption and thickness swelling, and accelerated aging. Valuable information can be obtained from these tests; however, they neglect the in-service exposure of wood-based materials to fluctuating hygrothermal loads. Although numerous authors have studied the effects of moisture on dimensional stability of wood-based panels, few (Johnson 1964; Wu and Lee 2002; Nofal and Kumaran 2003) have reported the effects of cyclic moisture loads. In those studies, the typical time-dependent behavior of MC and

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thickness swelling (TS) changes were not discussed.

The time-dependent response of wood-based materials has been widely reported in mechanosorptive studies (Martensson 1994; Wu and Milota 1995; Muszynski et al 2005; Olsson et al 2007). Creep, one component of the total mechanosorptive strain, refers to the progressive deformation of a material under constant load. It has been described using logarithmic, power law, and rheological models.

Logarithmic models were used by Ericksson (1967) to predict the deflection of chipboards after 27 yr using a short-term test of 30 da, but the creep deflection was underestimated. Gerhards (2000) successfully used a logarithmic model for wood beams under controlled and uncontrolled environments. Fan et al (2004) observed that logarithmic functions provided adequate fits for dimensional changes of cement-bonded particleboard subjected to cyclic RH changes. Power law models appropriately predicted creep of glulam and wood beams under cyclic humidity fluctuations (Hoyle et al 1986, 1994). Muszynski et al (2002) applied power law equations to calculate the viscoelastic component of phenol-resorcinol-formaldehyde resin under changing MC. Rheological models such as Maxwell, Kelvin, and standard linear solid models have been extensively used to portray the physical phenomena of time-dependent behavior (Pierce and Dinwoodie 1977; Mundi et al 1998; Nuñez et al 2004). Penneru et al (2006) demonstrated that the standard linear solid model closely fit the experimental data and adequately predicted the relaxation behavior of solid wood under compressive loading.

Most of the models discussed were used to describe viscoelastic responses either from mechanical or hygromechanical loading. They have not been applied to describe responses from solely cyclic humidity changes. An exception is the work of Fan et al (2004) on cement-bonded particleboard that has a different structure than conventional wood composites such as oriented strandboard (OSB) and thus the material response is expected to differ.

The most common approach to describe MC and thickness changes of wood products during different RH exposures is based on diffusion models. Below the FSP, moisture diffusion in wood occurs in two ways: diffusion of bound water through the cell walls and diffusion of water vapor through the void structure, including cell cavities and pit membrane pores (Dinwoodie 1981). The diffusion approach deals mainly with moisture transport in wood that obeys Fick's second law and is used to determine diffusion coefficients (Time 2002) or activation energies (Shi and Gardner 2006). Whereas the kinetics approach was found appropriate to describe the sorption process of wood, primarily in the hygroscopic range (Lu and Leicester 1997; Time 2002), its suitability has been questioned in wood-based products. Wood composites, because of stress relaxation that arises during moisture penetration, can have greater swelling than wood, causing prediction errors using a diffusion model (Shi and Gardner 2007).

We hypothesized that an empirical curve-fitting approach might be appropriate to develop models for the time-dependent behavior of wood composite panels under changing humidity conditions. We previously reported results of water-soaking tests (and mechanical properties) of OSB made of fire-impacted trees and bark (Moya et al 2008). The main objective of this paper was to study the MC and TS behavior of such products under cyclic RH changes. The specific goals were: 1) to establish a simple approach to analyze data from a test of wood-based panels exposed to alternating climate changes; and 2) to evaluate, using the empirical model, the effect of cyclic RH changes on the MC and TS response of OSB made of fire-affected trees and bark.

MATERIALS AND METHODS

Materials and Specimen Preparation

The experimental design and manufacturing details of panel-making were reported in a previous paper (Moya et al 2008) and are reviewed briefly as follows. Single-layer boards (560 ×

560 × 12.7 mm) were prepared using materials (strands and bark) from red pine (*Pinus resinosa*) trees with a wide range of damage from a very intense wildfire. A resin loading of 3.5% polymeric diphenylmethane diisocyante was used to prepare randomly oriented panels of 690 kg/m^3 average density. The boards were pressed at 200°C for 480 s, including 30-s closing, and 30-s opening times. Two 150- × 150-mm specimens were cut from the center of the boards. One was edge-sealed with a commercial edge sealant to study moisture sorption and TS for face-sorption vs face- and edge-sorption. Specimens were equilibrated at 20°C and 65% RH before testing.

A total of 16 treatments was designed to characterize panels made of four fire damage levels (BL1: unburnt, BL2: lightly burnt, BL3: moderately burnt, and BL4: severely burnt) and four percentage levels of bark addition (B0, B5, B10, and B20). For a specific burnt level (BL), both flakes and bark used in the panels came from the same log. Our previous work (Moya et al 2008) showed that addition of 20% bark (by weight) to the wood raw materials had a significant positive effect on the hygroscopic and dimensional stability (water absorption and thickness swelling) of the resulting OSB. The previous work also revealed that addition of lower percentages of bark did not significantly alter how water soaking affected the OSB dimensional stability. Therefore, the eight treatments that showed significant differences are discussed in this article: BL1-B0, BL1-B20, BL2-B0, BL2-B20, BL3-B0, BL3-B20, BL4-B0, and BL4-B20. The number of panels for each treatment was either 7 or 8 for bark-free boards and 4 for 20% bark-containing boards.

Cyclic Humidity Tests

All specimens were subjected to cyclic moisture variation of three moisture cycles at 20 ± 1°C. Each cycle was 4 wk at 90 ± 2% RH and 4 wk at 30 ± 2% RH. Before the first cycle, the panels were held at 30% RH for 4 wk. The high and low RH values were selected to reproduce extreme humidity changes expected for OSB in service.

Thickness measurements (±0.01 mm precision) were made weekly at four corners and the center of the specimens. The average of the five values was used to determine TS for each exposure interval during testing. Weight measurements (±1 mg precision) were taken at times corresponding to thickness measurements. At the end of the test, all specimens were oven-dried for 24 h at 105°C to calculate the oven-dry basis MC of each specimen corresponding to each weight measurement.

TS and MC at each time interval were determined according to the following equations:

$$TS(\%) = \frac{T_t - T_i}{T_i} \times 100 \quad (1)$$

$$MC(\%) = \frac{W - W_{od}}{W_{od}} \times 100 \quad (2)$$

where T_i = thickness at initial time (conditioned at 65% RH)

T_t = thickness measured at time t

W = weight

W_{od} = oven-dry weight

The MC change was reported as a ratio (MCR) in relative to the initial MC (MC_i) of the specimens conditioned at 65% RH:

$$MCR = \frac{MC}{MC_i} \quad (3)$$

MC Ratio and Thickness Swelling Modeling

Three models were adopted to describe the MCR and TS curves as a function of time (t):

Model 1: Logarithmic $y(t) = a + b\ln(t)$ (4)

Model 2: Power law $y(t) = c + at^b$ (5)

Model 3: Exponential based on rheological models

Kelvin + spring in series for the adsorption phase: $y(t) = c + a[1 - \exp(-bt)]$ (6a)

Maxwell + spring in parallel for the desorption phase: $y(t) = c + a[\exp(-bt)]$ (6b)

The coefficients of the respective models (a, b, or c) were determined by the nonlinear least-squares regression procedure. Eqs 4, 5, 6a, and 6b were fitted to MCR and TS experimental data at 90 and 30% RH.

Data Analysis

The data were analyzed based on a completely randomized block design in which the data were grouped into two blocks, edge-sealed and unsealed, to minimize variation within each group. Any significant differences in data at the end of the adsorption or desorption phase could then be attributed to the effects of treatments (burnt or bark addition levels). MCR and TS of the boards were the parameters to be compared ($\alpha = 0.05$), and the comparisons were performed using a two-factor analysis of variance (ANOVA). Tukey simultaneous pairwise comparisons ($\alpha = 0.05$) were then performed to discern the significance of difference between treatment means. Student's t tests were also conducted to investigate significant differences of model coefficients between cycles at $\alpha = 0.05$.

RESULTS AND DISCUSSION

MC and Thickness Swelling Behavior under Cyclic Humidity Exposure

Initial MC values ranged 3.7 – 4.8%, whereas initial thickness ranged 13.1 – 13.7 mm before the cyclic tests (at 65% RH). The MC and TS behavior of OSB control specimens (flakes from unburnt trees, bark-free) are shown in Fig 1. The MC or TS trends were similar for both unsealed and edge-sealed control specimens (Fig 1a – b). Two remarks can be made: 1) the most critical change occurred during the first week of each sorption phase, irrespective of whether it was adsorption or desorption; and 2) TS at the end of each adsorption or desorption subcycle progressively increased relative to the previous cycle. Furthermore, the edge-sealed specimen exhibited an apparently lower adsorption compared with the unsealed. At the end of the adsorption phase (end-point value) in Cycle 1, the edge-sealed specimens exhibited 10 and 24% reduction of MC and TS, respectively, compared with unsealed specimens. The MC and TS reduction trend was repeated in subsequent cycles. It should be noted that edge sealing has two effects: 1) it reduces the total surface area available for moisture transfer into and out of the specimen; and 2) it eliminates moisture transfer into and out of the edges. As stated by Fan et al (2006), the second effect is dominant because of the structural differences between edges and faces.

Our next attempt was to analyze the end-point values from the complete data set to compare hygroscopicity of OSB produced from various fire-impacted trees with or without the addition of bark. ANOVA showed that blocking successfully separated the effects of edge sealing (Table 1). Bark had some significant effects on the hygroscopicity and dimensional stability of OSB, whereas burnt level had no such effects. Bark and burnt level interaction was not significant. Boards with 20% bark showed MCR and TS values significantly lower than bark-free boards at the end of adsorption phase (90% RH) for all three humidity cycles. During desorption, bark had no significant effect in the first humidity cycle but became significant for TS in Cycles 2 and 3.

Model Comparisons: Closeness of Fit

To further investigate bark effects, the MC and TS behavior of corresponding OSB need to be examined throughout the humidity exposure cycles (as opposed to simply end points). This requirement warrants the use of models that describe the time-dependent behavior of MC or TS changes. To satisfy this need, we first compared the suitability of three time-dependent MC or TS models identified from the literature that were discussed in the "Introduction."

To ensure data representativeness, the experimental data of OSBs from four extreme treatments: BL1-B0 (control), BL1-B20, BL4-B0, and BL4-B20 (charred bark) were fit as separate

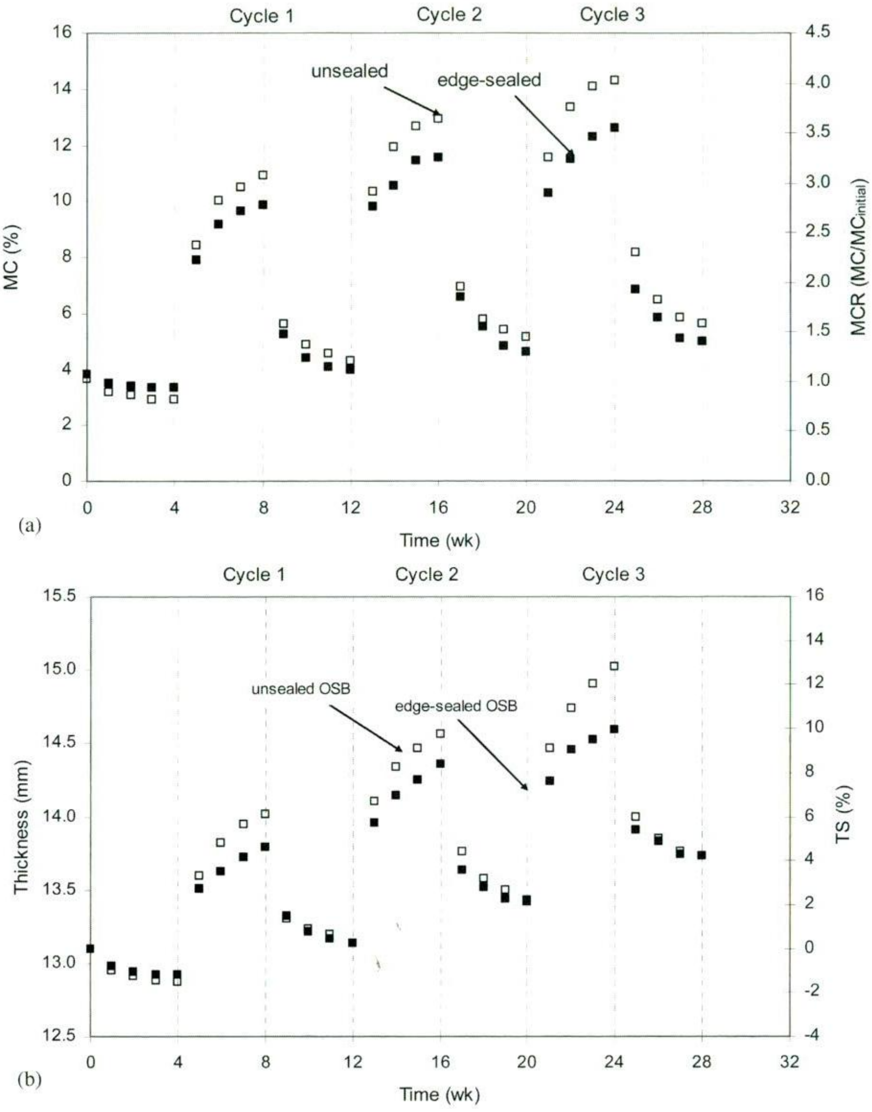

Figure 1. MC (a) and thickness swelling (b) behavior of control oriented strandboard under cyclic 90 – 30% RH exposure as a function of time. Each data point is the average of seven specimens.

curves. The curve-fitting attempts produced a range of values for the coefficient of determination (R^2) that indicate the respective degree of fit. R^2 values were determined by SigmaPlot 8.0 (2002). For MCR curve fitting, power law ($R^2 > 0.89$) and exponential ($R^2 > 0.89$) models fitted the data more closely compared with the logarithmic model ($0.77 < R^2 < 0.87$). Likewise, the power law ($R^2 > 0.97$) and the exponential model ($R^2 > 0.97$) fitted the experimental TS data better than the logarithmic model ($0.84 < R^2 < 0.93$). Based on the comparisons, the power law and exponential models were used for subsequent analyses.

Model Verification: Comparing Oriented Strandboard with and without Edge Sealing

To verify usefulness of the selected two models, we tested them on data of edge-sealed and unsealed OSB, both of which had different MC and TS behavior under cyclic humidity exposure (Fig 1).

Figure 2 compares the respective coefficient values of the power law and exponential models between edge-sealed and unsealed specimens. The *a* and *c* coefficients of unsealed specimens were significantly different from those of sealed specimens; however, edge sealing had no effect on the *b* coefficient.

In the power law model, the *b* coefficient is related to the rate of growth (or decay in the case of desorption) and gives its overall shape and behavior. Figure 3 shows a TS curve fit with a power law model (b = 0.32) and two hypothetical curves: one with the *b* coefficient one-half the value and the other curve twice the value of 0.32 with the *a* and *c* values fixed at 4.82 and –1.48, respectively. Except for a very brief initial adsorption, the curve with a higher *b* value exhibits a higher thickness increase. The

Table 1. *Analysis of variance results: MC ratio (MCR) and thickness swelling (TS) of oriented strandboard at the end of 90% and 30% RH cycles.*

	Cycle 1				Cycle 2				Cycle 3			
	End of 90% RH		End of 30% RH		End of 90% RH		End of 30% RH		End of 90% RH		End of 30% RH	
Source of variation	MCR	TS	MCR	TS	MCR	TS	MCR	TS	MCR	TS	MCR	TS
Block[a]	***	***	***	**	***	***	***	***	***	***	***	***
Burnt level[b]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Bark[c]	*	*	NS	NS	***	**	NS	***	***	**	NS	**
Burnt level × bark	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: NS = not significant; *, **, ***: significant at the 0.05, 0.01, and 0.001 levels, respectively.

[a] Block = edge sealed condition.

[b] Burnt level = assessment of fire damage to standing tree before harvest: 1, 2, 3, and 4.

[c] Bark (by weight percent) included in oriented strandboard: 0 and 20%.

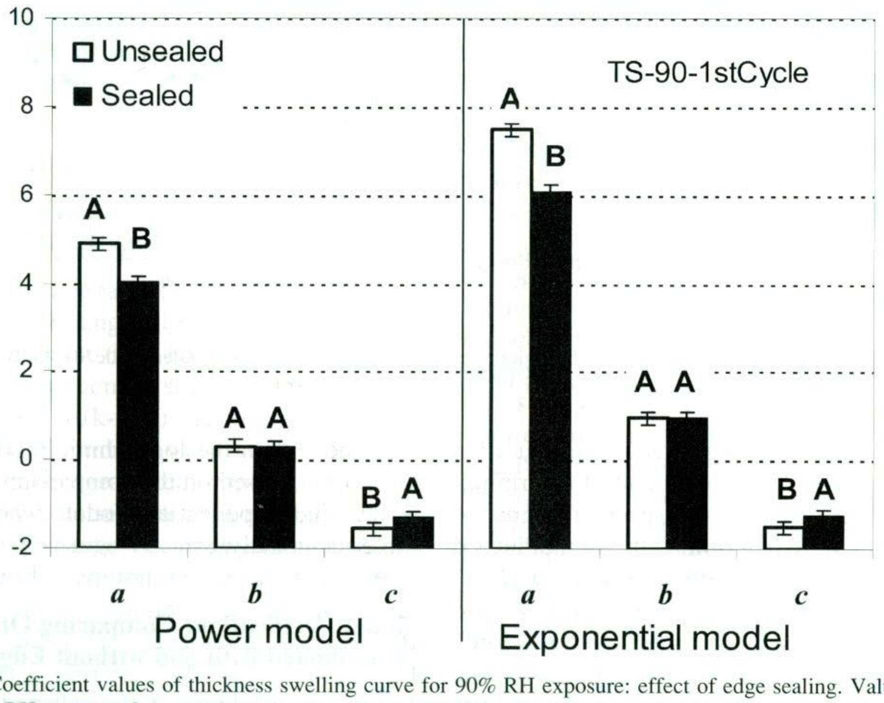

Figure 2. Coefficient values of thickness swelling curve for 90% RH exposure: effect of edge sealing. Values are from the first 90% RH exposure for control specimens (unburnt, 0% bark). Error bars are standard deviations; same letter (upper case) denotes statistically similar results ($\alpha = 0.05$) between column pairs.

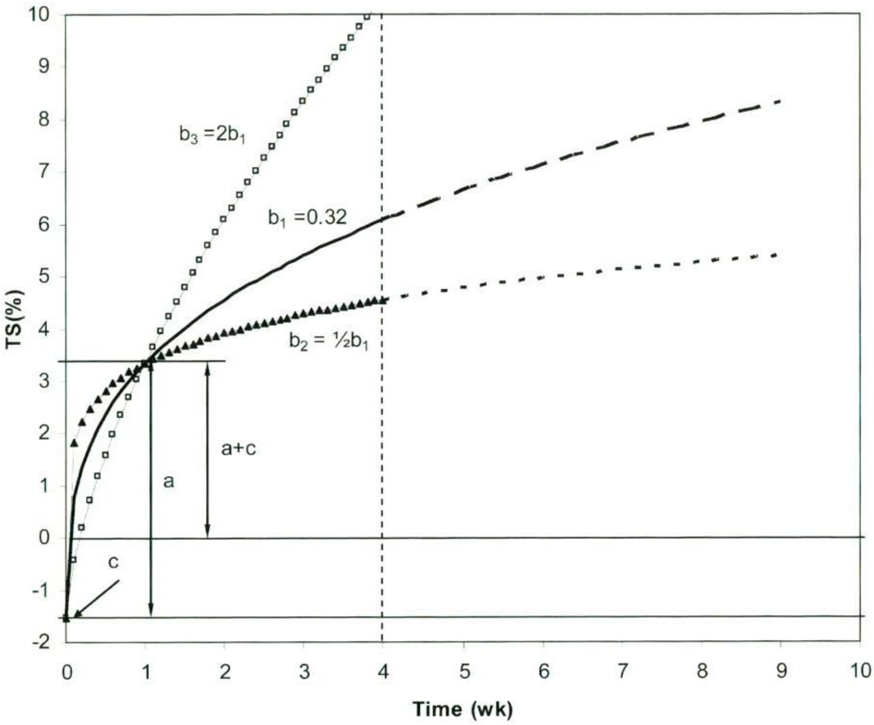

Figure 3. Thickness swelling (TS) curve for illustrating effect of coefficient b based on Eq 5: $TS = c + at^b$.

second coefficient, c, represents the intercept of the curve with the y-axis, which corresponds to the beginning of the adsorption or desorption cycle. The third coefficient, a, is a scaling factor that moves the values of t^b up or down as a increases or decreases, respectively. Figure 3 shows that the three modeled curves that have the same a value (4.82) intersect at Week 1 at a TS value (3.34%) that equals the value of "$a + c$" (ie 4.82 – 1.48). Thus, the a coefficient, in combination with coefficient c, provides information of the extent of TS (or MCR) increase (in Week 1).

Based on the understanding established, edge sealing (Fig 2) reduced the magnitude of TS at Week 1 (smaller a) and hence also reduced TS at the end of the adsorption cycle. The negative values of coefficient c in adsorption indicate that when the adsorption cycle began (at Week 4; Fig 1), both edge-sealed and unsealed specimens were thinner than the initial thickness at 65% RH because of the prior 30% RH desorption. However, the edge-sealed specimen after the initial desorption (65 – 30%) exhibited a final thickness closer to the initial (c value closer to zero; Fig 2) compared with the case of unsealed specimen, an indication of lower ability to lose moisture from edge sealing.

In the exponential model, a, b, and c coefficients have similar, although not identical, mathematical meanings compared with the previously mentioned reasoning for the power law model. Figure 4 shows a TS curve fitted with the exponential model ($b = 0.98$) and two hypothetical curves: one with the b coefficient one-half the value and the other curve twice the value of 0.98 with the a and c values fixed. The curve with a higher b exhibits a higher thickness increase and a shorter time to attain equilibrium. The extent of swelling at equilibrium is governed by the coefficient a. When a is fixed (6.09) for all three curves (Fig 4), the TS plateaus at a common level. This equilibrium (TS) level has a magnitude equal to the a value if the adsorption begins at zero TS. If the adsorption

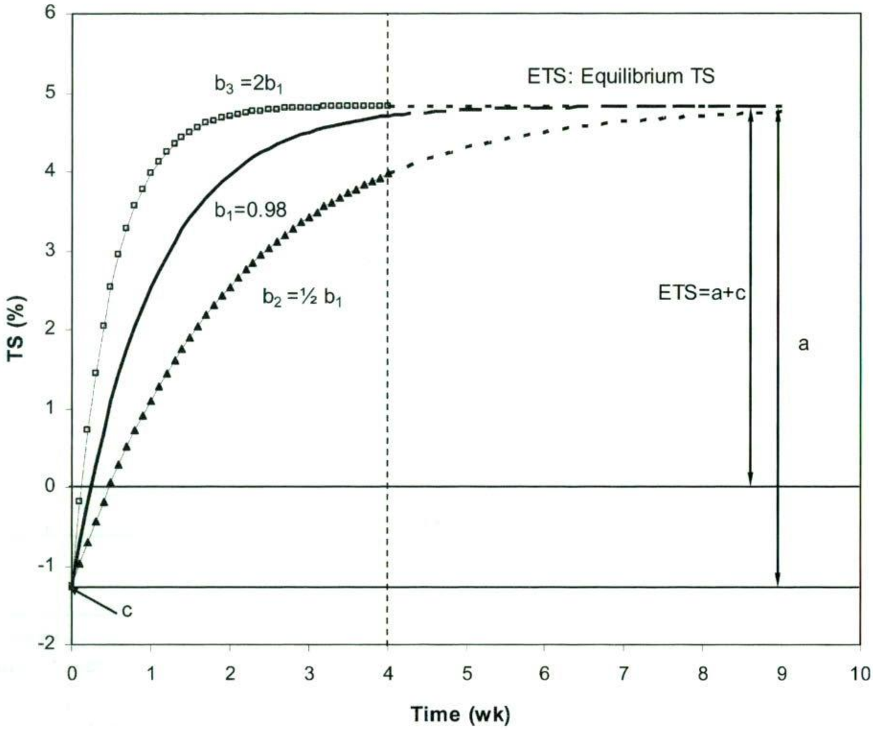

Figure 4. Thickness swelling (TS) curve for illustrating effect of coefficient b based on Eq 6a: TS = c + a[(1–exp(–bt)].

begins at a nonzero TS level (–1.26; y-axis intercept in Fig 4) represented by the *c* coefficient, the equilibrium TS (4.83%) has a value of "*a* + *c*" (ie 6.09 – 1.26).

Applying our established understanding of the exponential model, we concluded from Fig 2 that edge-sealing reduced the extent of swelling (lower *a*) during adsorption and decreased the thickness reduction at (the preceding) desorption (higher *c*). These conclusions are consistent with those of the power law model.

Model Application

Effects of bark on MC and thickness swelling cyclic changes. Power law and exponential models were applied to examine bark effects on OSB hygroscopicity and thickness changes throughout the humidity cyclic exposures. Values of the fitted coefficients for power law and exponential models are, respectively, shown in Tables 2 and 3. For all specimens, the *b* coefficients of MC change were similar to the *b* coefficients of TS change within a sorption subcycle (adsorption or desorption), and this behavior is commonly observed for both models. Statistical analysis also reveals that bark addition and burnt level did not alter the *b* coefficients of moisture sorption and thickness change of specimens.

When comparing treatment effects in humidity Cycle 1, charred bark addition to the OSB furnish (BL4-B0 vs BL4-B20, charred bark) resulted in lower values of the *a* coefficient for MCR and TS in adsorption. This behavior was commonly observed using both models, suggesting that the amount of thickness swelling of OSB was reduced by the addition of charred bark. In desorption, the same benefit of charred bark addition was observed wherein the (absolute) values of coefficient *a* were lower for MC and TS behavior in Cycle 1 (and subsequent cycles) for both models, a consistent indication of improved dimensional stability. Such an improvement in dimensional stability is not as

Table 2. *Fitted coefficients of the power law model for MC ratio (MCR[a]) and thickness swelling (TS[a]) changes of oriented strandboard in a series of cycles (90 – 30% RH) (model is: $y = c + at^b$).*

			Cycle 1					
			90%			30%		
	BL[b]	Bark[c]	a	b	c	a	b	c
MCR	1	0	1.42	0.30	0.775	−1.35	0.22	2.91
	1	20	1.26	0.29	0.789	−1.27	0.21	2.68
	4	0	1.50	0.29	0.725	−1.41	0.22	3.06
	4	20	1.22*	0.30	0.775	−1.25*	0.20	2.73*
TS	1	0	4.89	0.30	−1.55	−4.50	0.19	6.09
	1	20	4.63	0.31	−1.34*	−4.24	0.17	5.71*
	4	0	5.20	0.30	−1.51	−4.68	0.17	6.40
	4	20	4.21***	0.31	−1.25***	−3.96***	0.17	5.36***
			Cycle 2					
			90%			30%		
	BL[b]	Bark[c]	a	b	c	a	b	c
MCR	1	0	1.64	0.30	1.08	−1.75	0.22	3.48
	1	20	1.51	0.30	1.01	−1.52	0.21	3.29
	4	0	1.66	0.30	1.13	−1.75	0.22	3.62
	4	20	1.48*	0.31	1.08	−1.63	0.20	3.32*
TS	1	0	6.34	0.30	0.427	−5.82	0.20	9.83
	1	20	5.70	0.30	0.326	−5.74	0.19	9.00
	4	0	6.20	0.31	0.445	−6.07	0.19	9.88
	4	20	5.26***	0.31	0.399	−4.99***	0.21	8.44***
			Cycle 3					
			90%			30%		
	BL[b]	Bark[c]	a	b	c	a	b	c
MCR	1	0	1.79	0.31	1.26	−1.87	0.20	3.96
	1	20	1.66	0.30	1.23	−1.83	0.20	3.75
	4	0	1.84	0.30	1.27	−2.01	0.20	4.05
	4	20	1.70	0.31	1.18	−1.90	0.19	3.76
TS	1	0	7.03	0.30	2.15	−7.00	0.20	12.78
	1	20	6.88	0.31	1.47*	−6.64	0.17	11.87
	4	0	6.90	0.31	2.06	−7.24	0.16	12.52
	4	20	6.23***	0.30	1.90	−6.31**	0.17	11.31*

Note: Asterisks denote significant difference when compared with 0% bark within same BL. $*\alpha = 0.05$, $**\alpha = 0.01$, and $***\alpha = 0.001$.
[a] Mean values.
[b] BL: Burnt level = assessment of fire damage to standing tree before harvest: 1 = unburnt; 4 = severely burnt.
[c] Bark (by weight percent) included in oriented strandboard: 0 and 20%.

obvious in the case of adding undamaged bark to regular OSB flakes (BL1-B0 vs BL1-B20) that resulted in a lower (absolute) value of the *c* coefficient for thickness swelling (in adsorption) but did not statistically alter the (1) *c* value for moisture gain (during adsorption) and (2) *a* values for both moisture loss and thickness reduction during desorption (Tables 2 and 3).

To investigate MC and TS changes between consecutive cycles, the exponential model coefficients were compared. The exponential model was chosen for the need to know the equilibrium MCR (EMCR) or equilibrium TS (ETS) values, which are justified subsequently. Table 4 lists mean differences of the cycle-to-cycle comparisons for the exponential model. A positive mean difference indicates that the *a* or *c* value is mathematically larger compared with the previous cycle with an asterisk indicating statistical significance. Student's *t* test results showed that *b* remained constant from one adsorption or desorption subcycle to another (Table 4). The reciprocal of the coefficient *b*, so-called relaxation time (τ), was 1 wk for both MCR and TS in the adsorption phase. During desorption, the τ values were 0.75

Table 3. *Fitted coefficients of the exponential model for MC ratio (MCR[a]) and thickness swelling (TS[a]) changes of OSB in a series of cycles (90 – 30% RH) (model is: 90% RH: y = c + a[1-exp{–bt}]; 30% RH: y = c + a[exp{–bt}]).*

			Cycle 1					
			90%			30%		
	BL[b]	Bark[c]	a	b	c	a	b	c
MCR	1	2	2.13	1.02	0.783	1.79	1.31	1.12
	1	20	1.85*	1.05	0.799	1.64	1.37	1.11
	4	0	2.24	1.03	0.736	1.80	1.26	1.18
	4	20	1.90*	0.98	0.816**	1.60*	1.42	1.13
TS	1	0	7.50	0.96	−1.51	5.61	1.55	0.414
	1	20	6.96*	0.99	−1.30*	5.23	1.51	0.388
	4	0	7.77	1.00	−1.46	5.74	1.60	0.504
	4	20	6.63***	0.91	−1.22***	4.85***	1.59	0.454
			Cycle 2					
			90%			30%		
	BL[b]	Bark[c]	a	b	c	a	b	c
MCR	1	0	2.37	1.02	1.09	2.20	1.31	1.27
	1	20	2.24	1.01	1.02	2.00	1.32	1.25
	4	0	2.49	1.03	1.16	2.27	1.26	1.33
	4	20	2.21*	1.00	1.09	2.08*	1.43	1.24
TS	1	0	9.40	1.02	0.414	7.41	1.44	2.39
	1	20	8.54	1.03	0.375	7.25	1.48	1.73**
	4	0	9.30	1.00	0.494	7.70	1.46	2.17
	4	20	7.91***	0.99	0.443	6.44***	1.47	1.99
			Cycle 3					
			90%			30%		
	BL[b]	Bark[c]	a	b	c	a	b	c
MCR	1	0	2.69	1.02	1.27	2.48	1.34	1.47
	1	20	2.47	1.02	1.24	2.30	1.36	1.33
	4	0	2.76	1.03	1.27	2.59	1.29	1.40
	4	20	2.55*	0.99	1.19	2.38*	1.45	1.30
TS	1	0	10.51	1.00	2.20	8.93	1.43	3.83
	1	20	10.35	1.00	1.51*	8.09	1.62	3.77
	4	0	10.40	0.99	2.11	8.73	1.47	3.79
	4	20	9.31***	1.00	1.94	7.69**	1.59	3.60

Note: Asterisks denote significant difference when compared with 0% bark within same BL. *$\alpha = 0.05$, **$\alpha = 0.01$, and ***$\alpha = 0.001$.
[a] Mean values.
[b] BL: Burnt level = assessment of fire damage to standing tree before harvest: 1 = unburnt; 4 = severely burnt.
[c] Bark (by weight percent) included in oriented strandboard: 0 and 20%.

and 0.65 wk, respectively, for MCR and TS. Thus, specimens exposed to 30% RH are expected to attain EMC and ETS in less time compared with those exposed to 90% RH.

Table 4 shows: (1) the adsorption-induced moisture change reflected by the increasing *c* values was most dramatic in the first cycle; and (2) the desorption-induced moisture change appears to be reflected by the *a* values that increased in contrast to the unaltered *c* values at progressive humidity cycles. The inconsistent trends between *a* and *c* values are postulated to arise in that neither coefficient alone could represent EMC. Unlike the MC behavior, TS of all specimens exhibited cycle-to-cycle increase in either the *a* or *c* values. The uncorrelated moisture and thickness change is postulated to result from nonrecoverable (permanent) TS. The two postulations mentioned were scrutinized by calculating the EMCR and ETS.

Equilibrium MC ratio and equilibrium thickness swelling determination. The estimation of ETS (or EMCR) from a sorption curve is illustrated in Fig 5. The value of ETS after a

Table 4. *Mean difference in cycle-to-cycle comparison for coefficients a, b, and c from exponential model.*[a]

	BL	Bark	Cycle comparison	90% a	90% b	90% c	30% a	30% b	30% c
MCR	1	0	1 vs 2	0.241	—	0.304*	0.411*	—	0.144
			2 vs 3	0.325**	—	0.179	0.284	—	0.198
		20	1 vs 2	0.398*	—	0.234**	0.362**	—	0.139
			2 vs 3	0.224	—	0.218*	0.299*	—	0.083
	4	0	1 vs 2	0.256	—	0.420**	0.461**	—	0.146
			2 vs 3	0.263	—	0.117	0.325*	—	0.066
		20	1 vs 2	0.310**	—	0.275*	0.481***	—	0.109
			2 vs 3	0.339***	—	0.103	0.301**	—	0.065
TS	1	0	1 vs 2	1.895***	—	1.925***	1.792***	—	1.978***
			2 vs 3	1.110***	—	1.783***	1.526***	—	1.437***
		20	1 vs 2	1.581*	—	1.673***	2.020**	—	1.344**
			2 vs 3	1.805*	—	1.137***	0.842	—	2.034**
	4	0	1 vs 2	1.535***	—	1.957***	1.965***	—	1.670***
			2 vs 3	1.100**	—	1.614***	1.025**	—	1.616***
		20	1 vs 2	1.285***	—	1.661***	1.585***	—	1.531***
			2 vs 3	1.393***	—	1.496***	1.258**	—	1.617***

Note: Asterisks denote significant difference in the cycle comparisons: $*\alpha = 0.05$, $**\alpha = 0.01$, $***\alpha = 0.001$.

[a] Values are the differences in a given parameter from one cycle to the next, eg "a" for 90% RH in Cycle 2 minus "a" for 90% RH in Cycle 1.

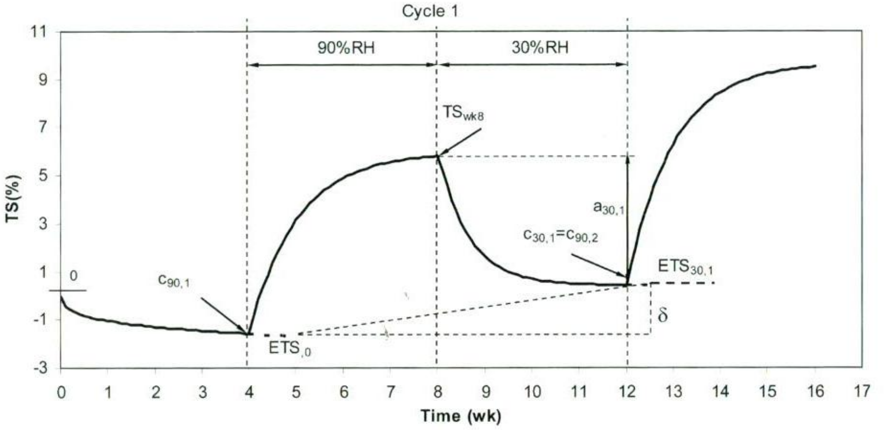

Figure 5. Exponential model curve of thickness swelling (TS) for unsealed oriented strandboard: Cycle 1. ETS: equilibrium TS; δ = difference in ETS values between end and beginning of one cycle.a_{90}: coefficient *a* from Eq 6a; a_{30}: coefficient *a* from Eq 6b.

complete 90 – 30% humidity cycle (ETS_{30}) is computed from the adsorption TS end-point value (TS_{wk8} for Cycle 1) and with the desorption *a* value (a_{30}). Using Cycle 1 as the example, the ETS after a complete 90 – 30% humidity cycle is given by:

$$ETS_{30-1} = TS_{wk8} - a_{30-1} \qquad (7)$$

Results of the calculations are presented in Table 5. The EMCR data closely match a standard sorption isotherm. Table 5 shows that at the end of Cycle 1 (30% RH), the EMCR levels became significantly higher (1.12 vs 0.78% for control specimens) compared with the initial 30% RH before the cyclic test.

Once the humidity was cycled further, the EMCR at the end of Cycles 2 and 3 (eg 1.26 and 1.45% MC for control specimens) became similar to that at the end of Cycle 1. These observations agree with the established knowledge of a sorption isotherm (Stamm 1964) in

Table 5. *Equilibrium MC ratio (MCR[a]) and thickness swelling (TS[a]) after a complete cycle (90 – 30% RH) calculated from the exponential model.*

	BL[b]	Bark[c]	Initial	End of Cycle 1	End of Cycle 2	End of Cycle 3	δ_2[d]	δ_3[d]
EMCR	1	0	0.782 A	1.122 A*	1.256 A	1.454 A		
		20	0.796 A	1.005 A**	1.241 A	1.329 A		
	4	0	0.728 B	1.168 A**	1.321 A	1.388 A		
		20	0.810 A	1.120 A**	1.223 A	1.3006 A		
ETS (%)	1	0	−1.553 A	0.378 AB***	2.268 A***	3.773 A***	1.890 A	1.505 A
		20	−1.333 B	0.329 B***	1.658 B***	3.763 A***	1.329 B	2.105 A*
	4	0	−1.503 A	0.492 A***	2.095 A***	3.785 A***	1.603 A	1.690 A
		20	−1.230 B	0.447 A***	1.922 AB***	3.553 A***	1.475 AB	1.631 A

Note: Same letter next to the value denotes statistically similar results at $\alpha = 0.05$.
Asterisks denote significant difference when compared with the previous cycle within the same treatment. $*\alpha = 0.05$, $**\alpha = 0.01$, $***\alpha = 0.001$.
[a] Mean values.
[b] BL: Burnt level = assessment of fire damage to standing tree before harvest: 1 = unburnt; 4 = severely burnt.
[c] Bark (by weight percent) included in oriented strandboard: 0 and 20%.
[d] δ: Refers to Fig 5; $\delta 1$ is not presented here because it is not entirely from nonrecoverable thickness swelling.

which (1) there is a hysteresis of EMC between the initial adsorption and desorption cycle at a similar RH; and (2) subsequent oscillating adsorption–desorption curves overlap.

Data in Table 5 prove the postulation in earlier discussions about the occurrence of nonrecoverable TS, often termed as true nonrecoverable TS (true NRTS). The true NRTS is a result of the combined effect of the springback and in-plane density variations (Suchsland 2004) that causes thickness to not return to its original value despite attaining the original MC level. In our study, there was an increase in ETS at the end of Cycle 1 compared with the end of precyclic desorption, but there was also a sorption hysteresis (difference in specimen MC; Table 5) that resulted in an apparent NRTS that is additional to the true NRTS effect. However, the true NRTS was evident at the end of Cycles 2 and 3 because the thickness did not recover fully to that of the previous cycle (eg 2.27% for control specimens at the end of Cycle 2 instead of 0.38%), although specimens were conditioned to the same MC level. Each additional humidity exposure cycle after Cycle 1 resulted in a similar amount of additional true NRTS ($\delta_2 = \delta_3$; Table 5).

The effects of bark and burnt levels can be also discerned from the equilibrium data at the initial desorption stage (Table 5). Generally, the primary differences between treatments occurred at the initial desorption stage before humidity cyclic tests. Indeed, at the end of each humidity cycle, the EMCR of various specimens was not significantly different. For thickness swelling, there were no statistical differences among specimens after two humidity cycles. Focusing on the initial desorption, burnt level showed no effects on TS. A comparison of bark-free boards (BL1-B0 and BL4-B0) reveals that the latter (OSB from severely fire-impacted trees) had a lower EMCR value indicating increased ability to lose moisture during desorption compared with OSB from unburnt trees. The slight decrease in EMCR did not cause a significant difference in thickness reduction between bark-free boards of BL1 and BL4. An unaffected TS was also reported based on a water-soaking test of OSB made of flakes from severely burnt trees (Moya et al 2008).

Data from the initial desorption suggest beneficial effects of bark addition on OSB dimensional stability. The lower ETS (absolute) value for boards of BL4-B20 (compared with BL4-B0; Table 5) verifies the favorable effect of charred bark suggested by the adsorption *a* and *c* coefficients in previous sections. When comparing boards of BL1 – 0% bark and BL1 – 20% bark, it was observed that the thickness reduction in the initial desorption was also decreased by the addition of unburnt bark to regular flakes. This beneficial effect of bark on panel dimensional stability is in agreement with the literature

(Nemli et al 2004; Moya et al 2008) and has been attributed to the higher percentage of the hydrophobic lignin present in bark compared with wood and from extractives from bark.

Our earlier discussions established that computed data of equilibrium MCR and TS (Table 5) at the initial desorption (before cyclic tests) are useful in discerning bark effects. It is noteworthy that these initial equilibrium data are also provided by $c_{90,1}$, the c coefficient for adsorption in Cycle 1 (see Table 3), which traces back to experimentally measured MCR or TS values of conditioned specimens before the cyclic humidity test. A logical question that follows is whether a model is needed to make the same conclusions on bark effects. To address this issue, we examined the experimental end-point data of adsorption, represented also by c_{30}, the starting point of the subsequent desorption (30% RH). The cycle-to-cycle changes in c_{30} (Table 4) are compared with the cycle-to-cycle changes in the calculated (predicted) equilibrium MCR or TS values (Table 5). Both data sets are comparable for all treatments except one: the charred bark-containing boards exhibit a significant increase in c_{30} (Table 4) for MCR from one cycle to another but show a consistent equilibrium MCR (Table 5) after Cycle 1. This exception verifies the postulation in earlier discussions about no single a or c coefficient could represent EMC. Additionally, it signifies the importance of measuring equilibrium specimens or, in the case of insufficient cyclic duration, predicting the equilibrium (MCR or TS) value. It follows that the time-dependent (exponential) model is useful in providing the b coefficient as a relative measure of the sorption or thickness rate, and also the a and c coefficients for computing (predicting) the MC or TS at equilibrium in a humidity exposure cycle.

CONCLUSIONS

A simple approach for analyzing and modeling MC and TS data from OSB exposed to alternating climate changes was proposed. Power law and exponential models were found appropriate to describe MC and TS behaviors. Both models provide a coefficient b that relates to the rate that sorption or thickness changes occur during the cyclic exposure. Specifically, the exponential model provides coefficient a as a relative measure of the amount of sorption or thickness change behavior and also, if needed, the quantitative (predicted) MC or TS at equilibrium.

From this research, the following conclusions can be drawn for three consecutive cycles of 90 – 30% RH exposure:

- The most critical change in MC or TS occurred during the first week of the sorption phase, irrespective of adsorption or desorption.
- Edge sealing of OSB did not affect swelling rate but efficiently reduced the extent of moisture gain and swelling during adsorption, and decreased the thickness reduction and moisture loss at desorption. Approximately 10 and 24% decreases were observed for MC and TS, respectively, at the end of adsorption in the first cycle.
- OSB from severely burnt trees did not exhibit a significantly different dimensional stability compared with OSB from unburnt trees.
- Bark addition did not impact the rate of thickness swell and MC change during the 90 – 30% RH cyclic exposure. However, addition of charred bark was found to be beneficial for OSB moisture and dimensional stability.
- Panels exhibited equilibrium TS at the end of each 90 – 30% RH cycle. The presence of apparent nonrecoverable TS at the end of Cycle 1 from sorption hysteresis hindered the observation of true nonrecoverable TS. However, the nonrecoverable effect was evident after Cycle 1 with each additional cycle resulting in a similar additional amount of true nonrecoverable TS.

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